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The Effect of Monomolecular Films on the Underlying Ambient-Noise Field

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A series of at-sea tests have unequivocally established that the presence of a monomolecular surface film results in a pronounced reduction of ambient noise beneath the film. This reduction was observed over a wide range of surface conditions associated with sea states 1 through 6. Possible mechanisms through which the film affects the underlying ambient-noise field are explored.

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SUMMARY

OBJECTIVE

Assess the effect of monomolecular films, spread on the ocean's surface, on the underlying ambient-noise field.

RESULTS

A series of at-sea tests have demonstrated that beneath the area slicked by film, local surface-generated noise from about 2 kHz to at least 20 kHz is dramatically reduced. This behavior was generally observed throughout sea states $1\frac{1}{2}$ to 6.

RECOMMENDATIONS

Further at-sea measurements are needed, particularly at low sea states, to determine the noise mechanism which the film affects.

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INTRODUCTION

Practical applications of monomolecular films (surfactant chemicals which tend to form a layer, 1 molecule thick, on the water's surface) extend throughout recorded history. As early as the ninth century B.C., sponge divers would spread olive oil (containing the surfactant oleic acid) on the water surface in an attempt to increase visibility underwater (Young, 1983). The photographic and irradiance data of Barger and Garrett (1974) have shown no significant visibility enhancement beneath similar slicks. However, the smoothing effect of the film on the water surface was found to eliminate the flickering patterns of sunlight focused by the surface ripples, which would be distracting to the human eye. Aristotle had described the seaman's practice of attempting to calm waves in a storm by pouring oil onto the sea (Scott, 1977). Although throughout history there have been numerous anecdotal accounts that surface films have dramatically reduced wave breaking during storms, there have been no definitive experiments at high sea states to verify this. Scott (1987) argues that by reducing the surface roughness of the large waves, thereby decreasing the aerodynamic drag exerted by the wind, surface films could possibly diminish the probability of a given wave breaking. A similar line of reasoning was previously espoused by Benjamin Franklin (1774, p 449), who performed the earliest scientific experiments on the effect of oily films on water. In 1774, Franklin read a paper to the Royal Society in which he described his famous experiment on the Clapham Common. Applying less than a teaspoon of oil to the half-acre pond, which was "very rough with wind," it became "as smooth as a looking glass." Surface films have since been shown (Barger and Garrett, 1970; Huhnerfuss and Garrett, 1981) to play an important role in many other air-sea interaction processes e.g., evaporation retardation, foam stability, and wind-wave dynamics.

In 1880, Osborn Reynolds (1880) conjectured that the calming effect of oil on capillary waves is due to the variations of surface tension resulting from the undulations of the contaminated surface. When the surface is compressed and extended, the local surface tension fluctuates as a consequence of the changing number of absorbed film molecules per unit area. This produces an alternating tangential drag on the water in the microlayer just beneath the surface which results in an increase in dissipation.

Concerning the film's impact on ambient noise, theoretical arguments proposed by Glazman (1985) predicted that surface-active materials, adsorbed onto microbubbles, could have an important influence on the low-frequency (under 1 kHz) properties of the subsurface ocean layer. There has also been speculation (Davis et al., 1986) that films may have an influence at higher frequencies through their effect on the noise generated by splashes. An at-sea study of the surface film's effect on ambient noise from 0 to 20 kHz is unique to this investigation.

In the deep ocean, the natural ambient-acoustic-noise level from about 0.5 to 25 kHz is related to wave height and wind speed (Knudson, Alford, and Emling, 1948; Wenz, 1962; Kerman, 1984). Although no consensus exists as to the exact physical mechanisms that produce this noise, it is generally agreed that the mechanisms are natural phenomena operating at or very near the sea surface *in the vicinity of the* observation. It was hypothesized that the reduced surface agitation produced by a monomolecular film could reduce the ambient-noise level of a sensor directly below. The exceptionally large spreading areas per unit volume of these materials further encouraged at-sea testing. Theoretically, 1.7 liters of oleyl alcohol, a representative material, should cover 1 square kilometer. Furthermore, it is nontoxic and reacts very slowly with sea water, if at all.

ACOUSTIC MODELING

It was not known *a priori* what the effect of a surface film would be on ambient-sea noise. As a precursor to the at-sea investigations, propagation modeling of ocean surface-acoustic noise was conducted to determine the principal frequencies impacted, the optimum size of slick, depth of sensor, and an indication of the noise-reduction benefits.

The model used is an extension of the ambient-sea-noise model proposed by Talham (1964). In the present version, the ocean bottom is considered flat and horizontal and the sound-speed profile is independent of horizontal position. These are two reasonable assumptions, considering the relatively short horizontal ranges *within which most of the surface noise* above 0.5 kHz originates.

A series of ray paths are traced from the location of the receiver and form successive rings of intersection with the surface. Propagation losses from geometric spreading, estimates of volume absorption, bottom loss, and surface scattering are then calculated from these rings at the surface back to the location of the receiver.

The sound-speed profile shown in figure 1a is used for an illustrative example. The upper portion of this profile is calculated from a temperature profile measured during one of the experiments. The lower portion is historical data from the general area. There was no surface duct in this case. In figure 1b are the corresponding ray paths traced from the location of a receiver at a depth of 122 meters, a depth representative of much of the experimental data collected. In this environment, there are only direct paths between the ocean surface and the receiver out to a horizontal range of a little more than 1 kilometer. Beyond that, the surface is in a shadow zone from the receiver, and the only connecting ray paths reflect over a moderately lossy bottom at a depth of 1500 meters.

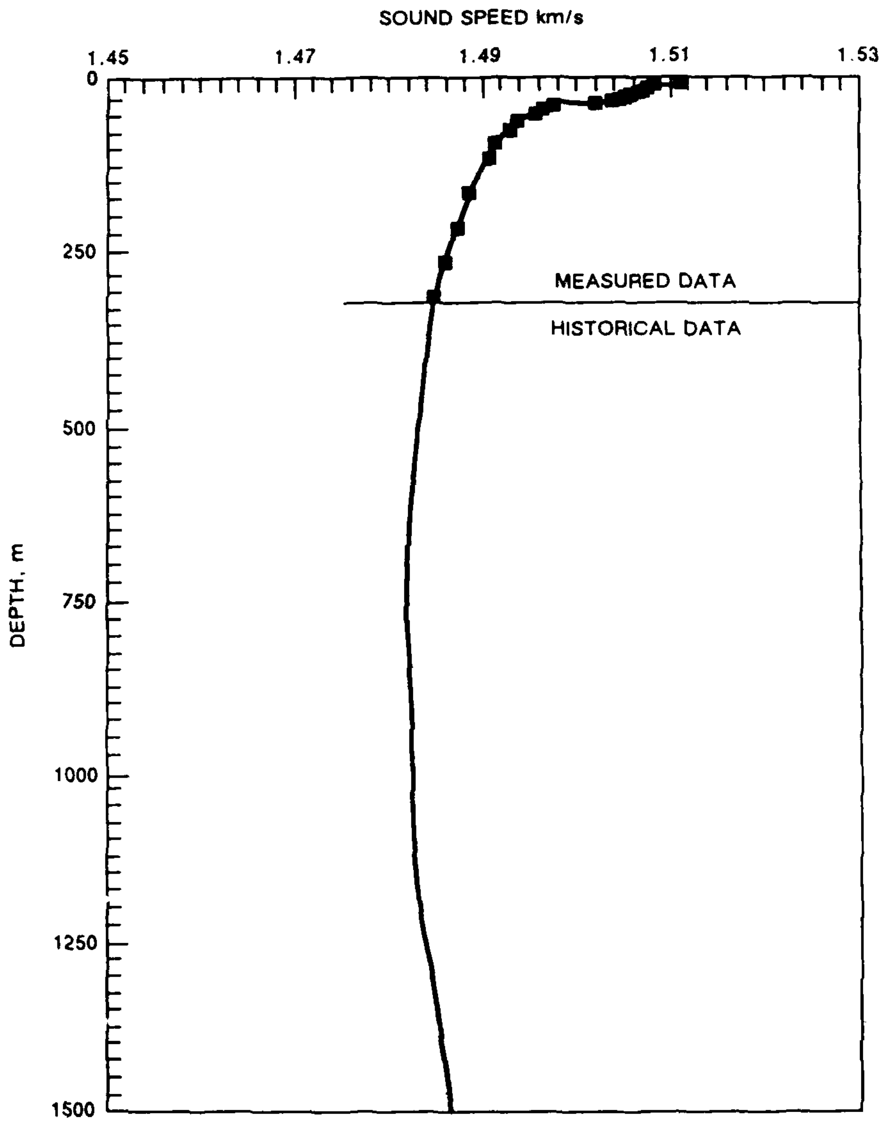

Figure 1a. Sound-speed profile used to illustrate model predictions.

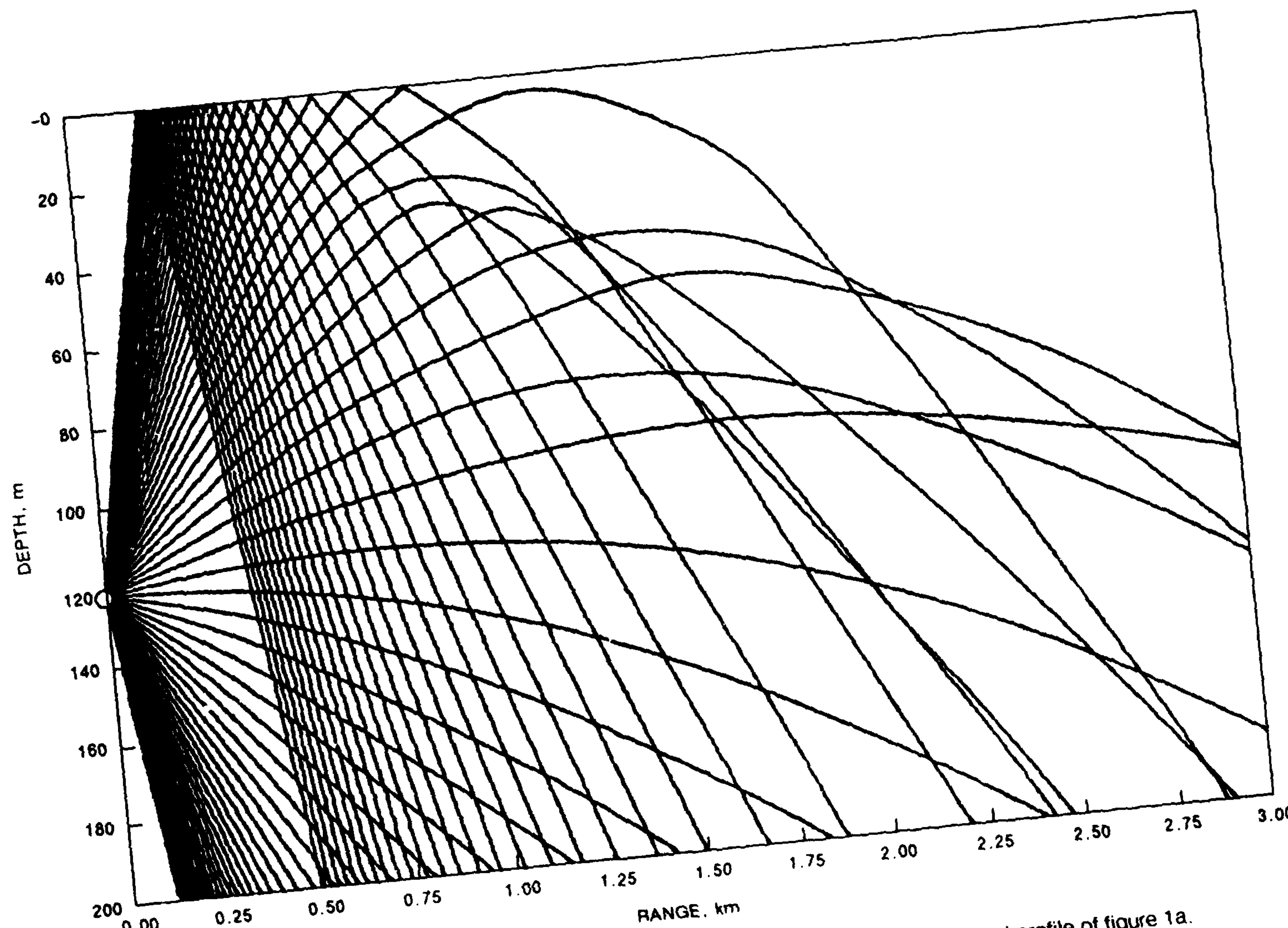

Figure 1b. Rays traced from a source at 122-meter depth using the sound-speed profile of figure 1a.

There are many ways in which outputs from the propagation model for this example can be presented. Figure 2a represents the fraction of the total surface-noise power received by a hydrophone 122 meters below the surface, as a function of horizontal range (i.e., surface radius) for acoustic frequencies of 0.5, 1, 2, 4, and 8 kHz. In figure 2b the depth dependence of this fraction is compared for sensors at 18- and 122-meter depths at an acoustic frequency of 6 kHz.

The model calculations, which were performed for a variety of anticipated sound-velocity profiles, provide general insight. At low frequencies there is relatively low propagation loss other than geometric spreading, and surface noise can propagate long distances. At 0.5 kHz in the previous example (see figure 2a), half of the surface noise energy originates from horizontal ranges greater than 1100 meters and arrives at the hydrophone over bottom-bounce paths. It is only at the higher frequencies where dissipative propagation losses are effective that surface noise is dominated by sources at short ranges. Figure 2a also shows that a film of 250-meter radius covers 83 percent of the source of noise energy at 8 kHz, but only 30 percent of the source of noise energy at 0.5 kHz.

By comparing the model results for surfaces with and without films, and assuming the film could be several hundred feet wide and suppress half the surface noise where it spread, estimates for the ambient-noise-quieting benefits were made. These were found to lie well within our measurement capabilities for a wide range of slick coverage.

There is a knee in the curves of figures 2a and 2b, typically at a horizontal range near twice the sensor depth. The sensors in the experiment could be set at either 18- or 122-meter depths. It was inferred from model calculations (of which figures 2a and 2b are representative) that whatever the noise-suppressing effect a 300-meter radius film centered above the hydrophones may have, further increasing the area covered would not increase the benefits significantly. Therefore, surface films roughly 300 meters in radius were considered desirable for the experiments.

AT-SEA TESTS

The objective of the at-sea tests was to determine the impact of monomolecular films in reducing local surface-generated noise in the open ocean. A series of sea tests have been successfully conducted throughout a wide range of sea states. The basic format of each test was to deploy a pair of omnidirectional hydrophones at 18- and 122-meter (60 and 400 feet) depth settings to provide an ambient noise reference. One or more tethered test pairs of hydrophones were then deployed about 4 miles away from the reference pair at similar depths. To minimize contaminating the sound field by noise from the monitoring platform, the response of the hydrophone was converted to an RF signal and transmitted (via an antenna fixed to the hydrophone buoy) to a distant aircraft. Around each test pair is deployed 10 to 15 gallons of an organic chemical resulting in slicks estimated to be 300 to 350 meters in radius.

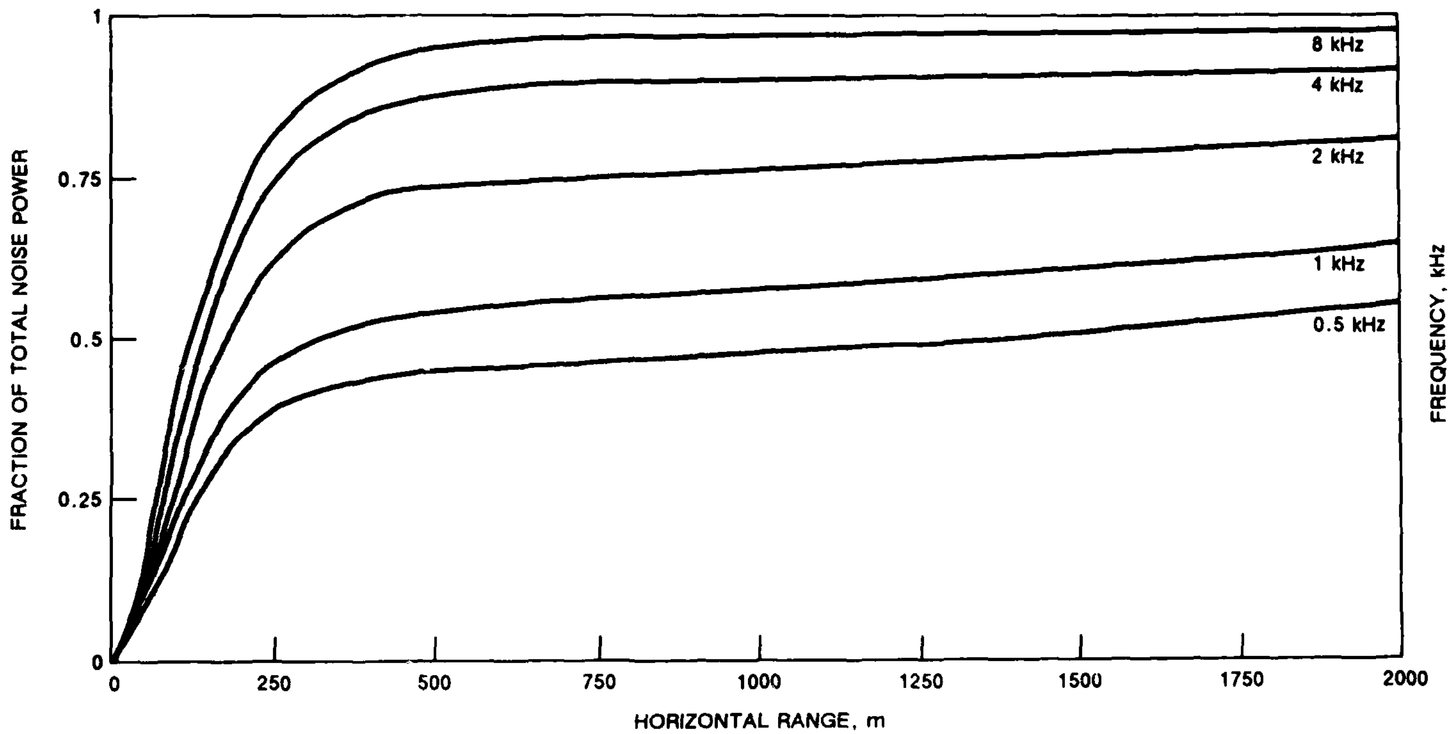

Figure 2a. Predicted fraction of the total noise power at frequencies 0.5, 1, 2, 4, and 8 kHz, as a function of the horizontal range within which it originates as determined by the sound-speed profile shown in figure 1a. The sensor is located 122 meters below an assumed homogeneous *surface distribution of dipole noise sources.*

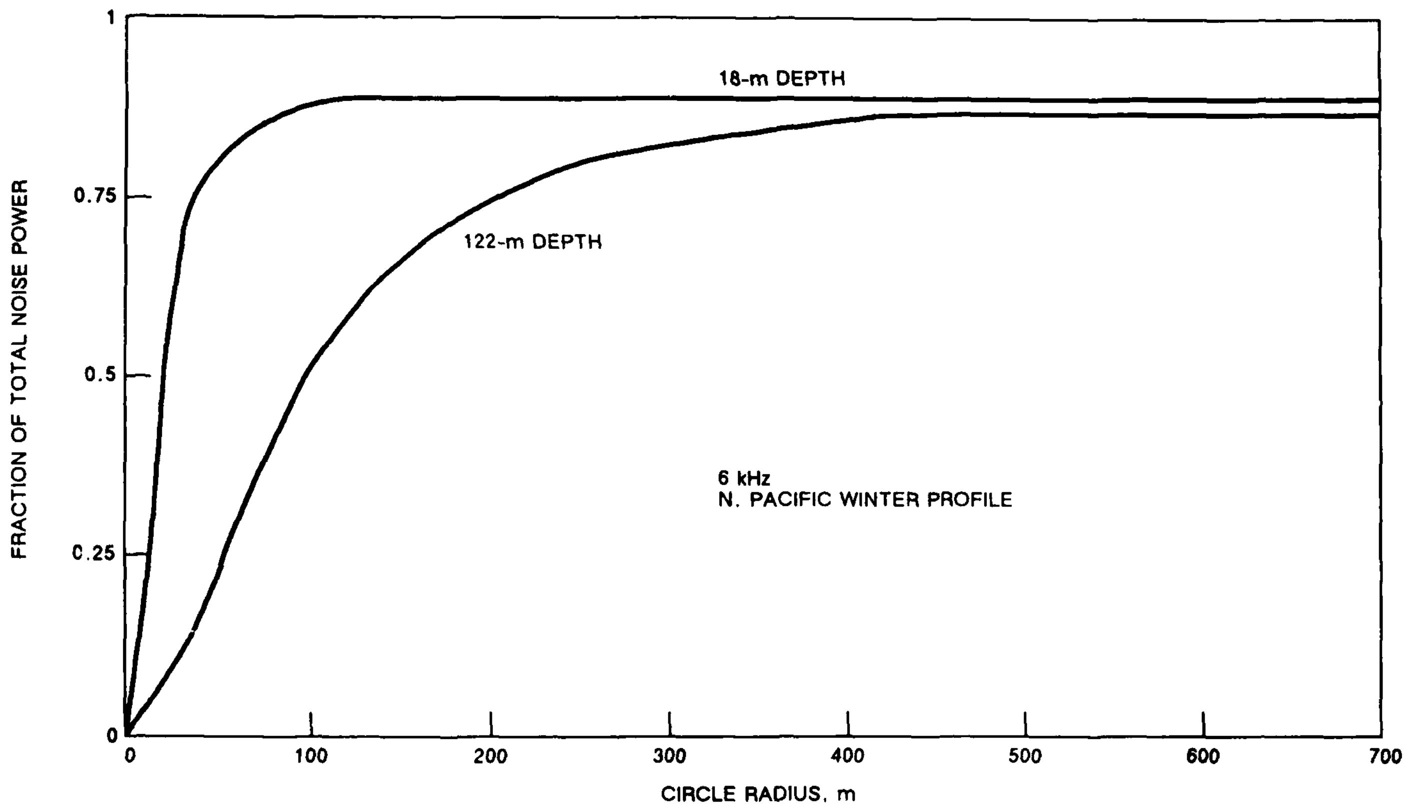

Figure 2b. Predicted fraction of the total noise power at 6 kHz, for depths of 18 and 122 meters, as a function of the horizontal range within which it originates as determined by the sound-speed profile shown in figure 1a. Sensors are assumed to be beneath a homogeneous surface distribution of dipole noise sources.

The principal chemicals tested have been oleyl alcohol (9-octadeen-1-ol, cis isomer) and a doubly ethoxylated isosteryl alcohol (tradenames ADOL-85 and AROSURF-MSF respectively). These chemicals are nontoxic, essentially insoluble, biodegradable surfactants. ADOL-85 is used in cosmetics and resembles natural slicks in its physicochemical behavior (Huhnerfuss, et al. 1981b). AROSURF-MSF is used on drinking reservoirs for mosquito control (Levy, 1984) (by decreasing surface tension the film prevents the insect from resting, breathing, and molting on the water surface). Since surfactant molecules are composed both of a hydrophilic and hydrophobic end, they tend to spontaneously spread over the water, forming a layer only 1 molecule thick. For the present experiments the volume of chemicals deployed was about ten times more than theory dictated to cover an area of a 300-meter radius. This allowed the chemicals, which do not spread readily on themselves (autophobic), to form tiny reservoirs which replenish tears in the films as a result of the wind and waves.

The chemicals were sprayed from a helicopter as it slowly spiraled out to the desired radius. As a check for possible shear degradation, similar chemicals were continually recycled through an identical dispensing system in the laboratory where infrared spectral analysis and viscosity measurements were taken. No indication of any alteration of either chemical by the dispensing system was observed. Normally, between the self-spreading properties of the films and the maneuverability of the helicopter, within 10 to 15 minutes after initial deployment, an uninterrupted film could be seen on the ocean surface (e.g., figure 3). Visual confirmation of the slick at high sea states was reduced due to the attendant poorer visibility. At the lowest sea states, where the ocean surface was naturally unruffled, the application of the chemicals could not be visually determined at all. This is not unexpected since the film, being only a few nanometers thick, cannot be directly observed nor will it exhibit optical interference properties. From a distance, the film's presence can only be visually inferred from its surface-smoothing effects, which are most conspicuous along its perimeter.

Except for the ramifications of the surface-smoothing effects of the film, the experimental design is intended to provide nearly identical ambient-noise environments between the reference hydrophones and the test hydrophones beneath the slick. Often, this was thwarted by spatial variability in surface vessel traffic and weather conditions (squalls), buoy washover (at higher sea states), schools of squealing porpoises, and RF interference. The resulting intermittency precluded a continuous, unblemished temporal comparison between reference and test hydrophones. However, the slick duration was long enough to provide a series of 1- to 2-minute intervals free of the aforementioned anomalies which was detected either aurally or by observation of the unintegrated spectra on either the test or reference channel. None of these tests were designed to maximize slick persistence above the sensors, consequently persistence was quite variable being a function of current, wind, and wave action, as well as the accuracy of the initial slick deposition. Slick duration varied between 15 to 90 minutes decreasing with increasing sea state as expected. The tests are summarized in table 1.

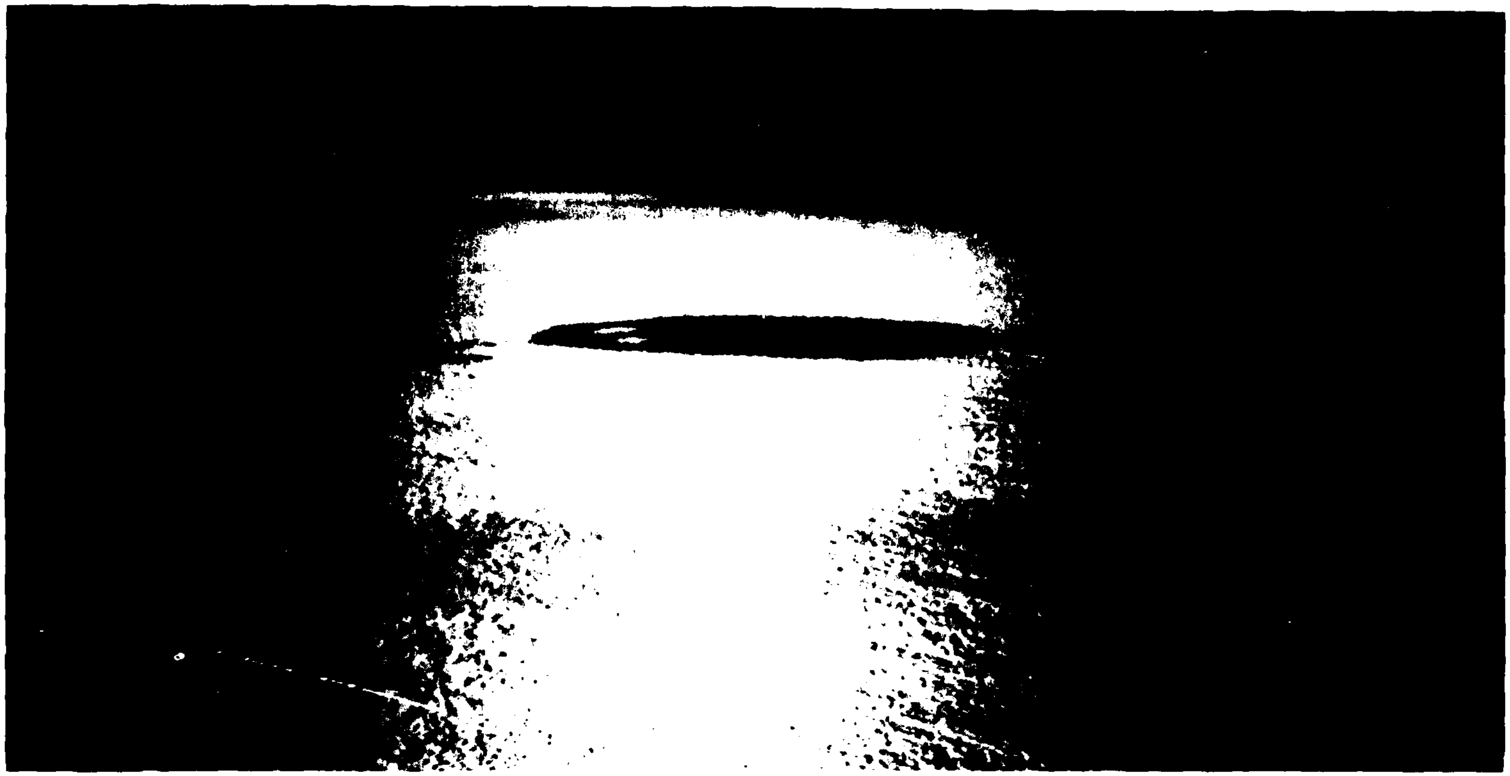

Figure 3. Photograph of slick taken in a sea state $1\frac{1}{2}$.

Table 1. Test summary.

Experiment	Sea State	Wind Speed (knots)	(meters)	Objective
I	~$1\frac{1}{2}$	~6	~3	Initial test of hypothesis
II	~2	~10	~5	Confirm initial results
III	~5-6	~30-50	~15-26	Test in high sea states
IV	~0	~1	0.5	Test in low sea state

AT-SEA TEST RESULTS

Data processing was performed using a Spectral Dynamics SD-375 dual-channel digital spectrum analyzer. Simultaneous individual spectra and spectral ratios (test/reference at identical depth setting) were computed over a 0- to 20-kHz range. The averaging time for these spectral ratios varied between 1 to 2 minutes depending on the intermittency of the previously mentioned unwanted noise. The observed spectral ratios as a function of time after slick deployment for experiments I through III are summarized in figures 4 through 12 and are expressed in dB, i.e., 20 log (output spectral amplitude of test hydrophone in slick/output spectral amplitude of reference hydrophone outside slick). The sensitivity and gains of the test and reference hydrophones did not vary significantly as demonstrated by their initial near zero spectral ratio throughout most of the frequencies of interest before the slick was generated (e.g., top of figure 12). Later, as the effect of the deployed slick diminished, there was generally observed a gradual return to this initial near zero value of the spectral ratio. The sea state was assessed by visual observation and generally substantiated by local weather reports.

Results from experiment I, which utilized a single slick of AROSURF-MSF in a sea state $1\frac{1}{2}$ (about 6 knots), are shown in figures 4 and 5. Some general features to note are

a. At frequencies below 2 kHz the spectral ratios may exhibit large variability due to spatial inhomogeneities in the surface vessel traffic in the test area.

b. For higher frequencies the noise-suppression effect of the film is always clearly evident, as expected from the model. Surprisingly, the film's quieting performance at the highest frequencies measured appears here (and also for higher sea states) to fall noticeably short of the model prediction. This anomaly will be discussed later, when ADOL-85's results can be compared.

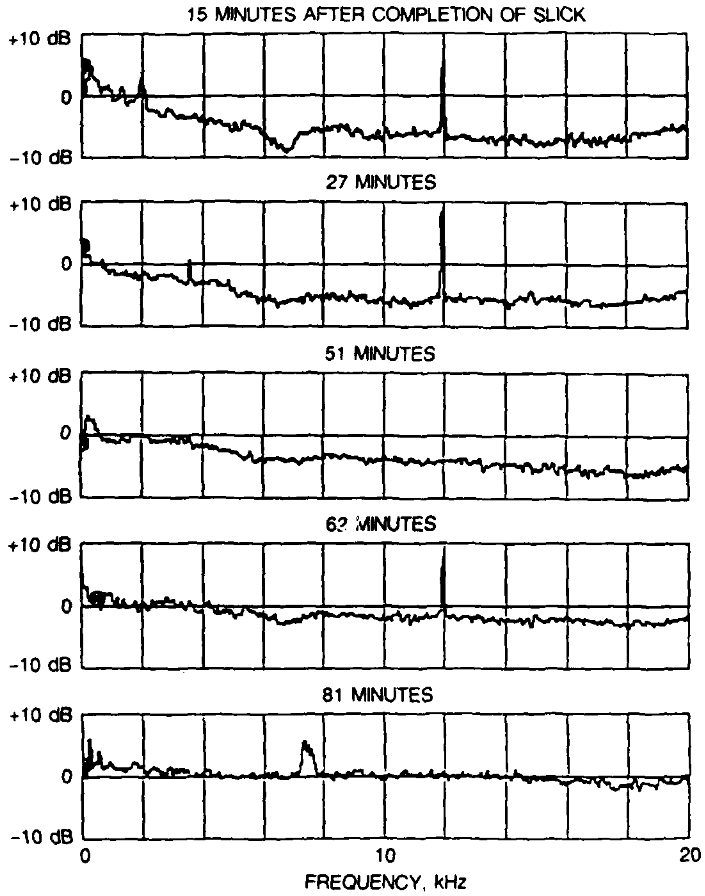

Figure 4. Spectral ratios (slick/no slick) for AROSURF-MSF, sensors at a depth of 18 meters in a sea state $1\frac{1}{2}$.

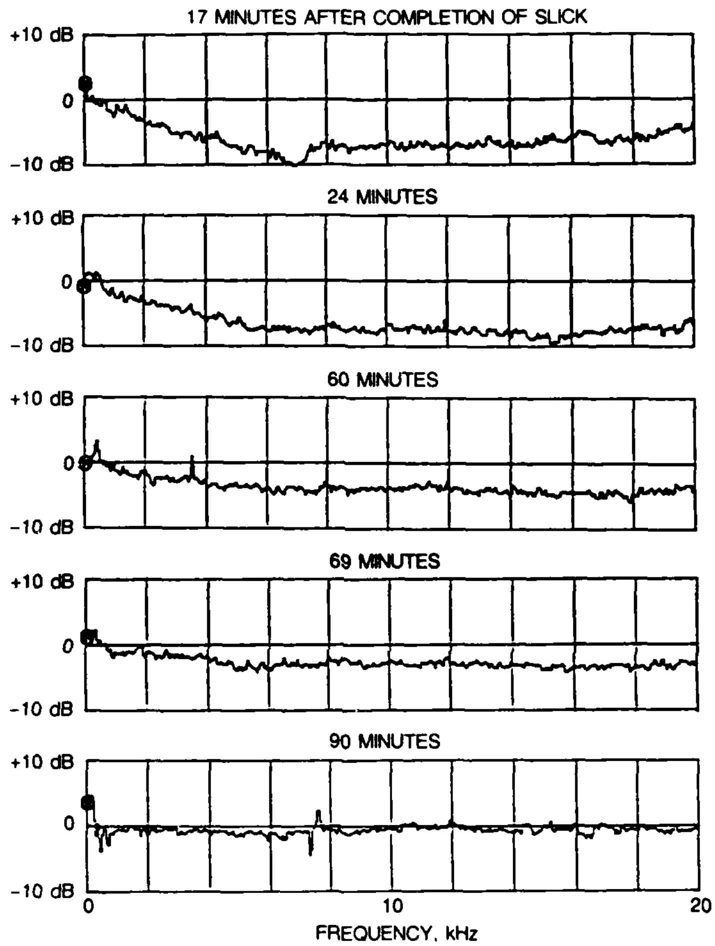

Figure 5. Spectral ratios (slick/no slick) for AROSURF-MSF, sensors at a depth of 122 meters in a sea state $1\frac{1}{2}$.

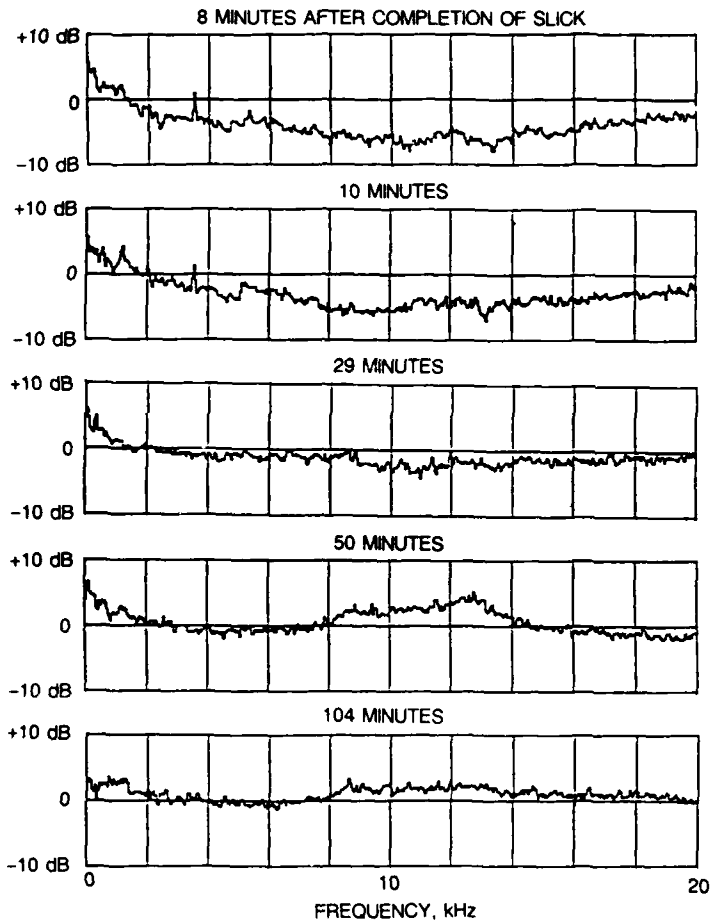

Figure 6. Spectral ratios (slick/no slick) for AROSURF-MSF, sensors at a depth of 18 meters in a sea state 2.

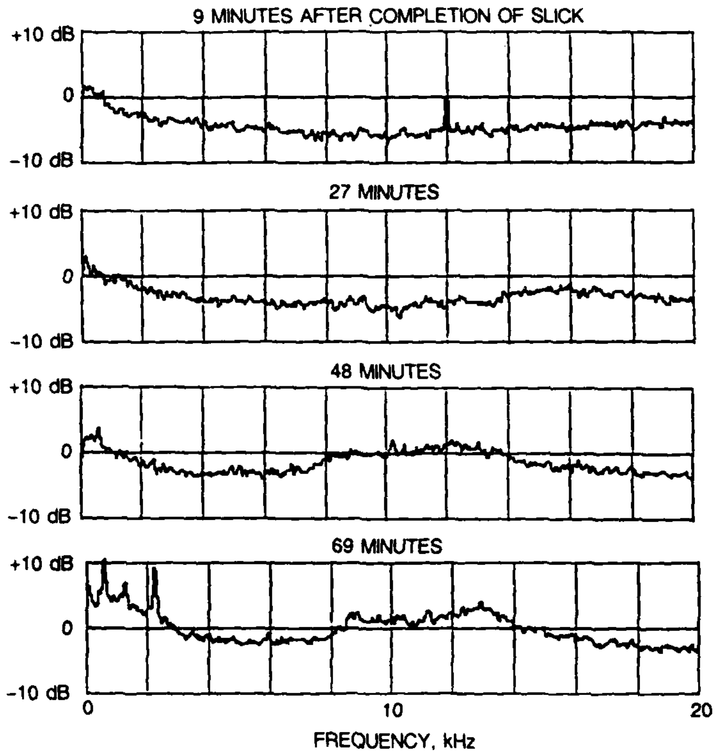

Figure 7. Spectral ratios (slick/no slick) for AROSURF-MSF, sensors at a depth of 122 meters in a sea state 2.

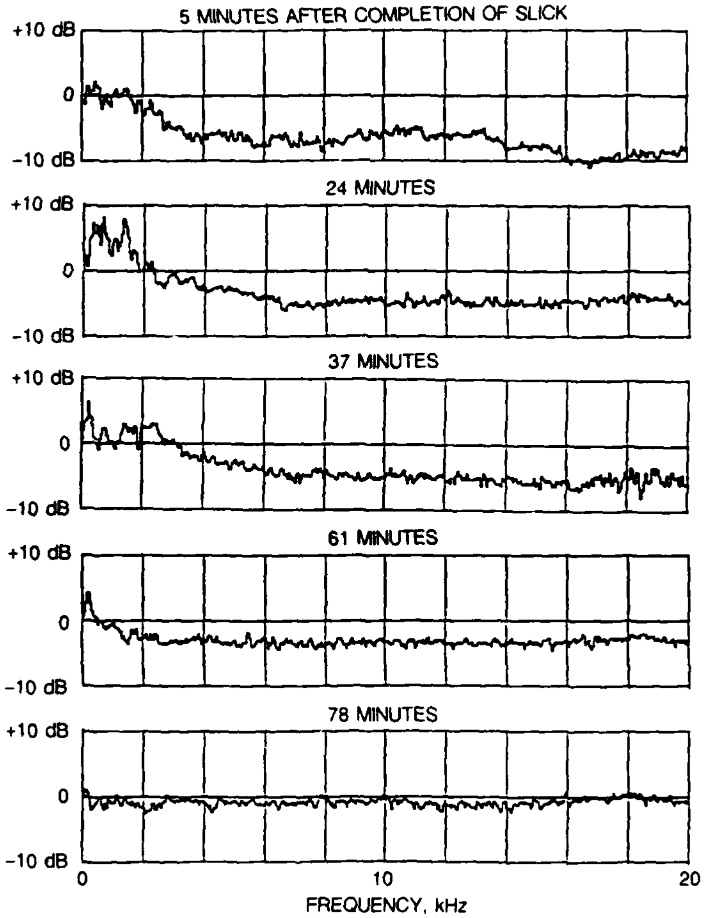

Figure 8. Spectral ratios (slick/no slick) for ADOL-85, sensors at a depth of 18 meters in a sea state 2.

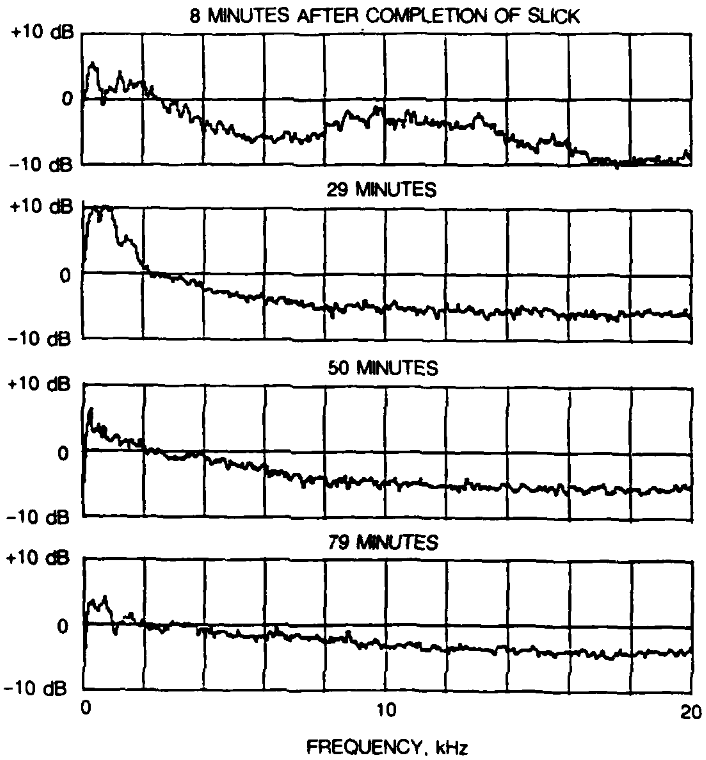

Figure 9. Spectral ratios (slick/no slick) for ADOL-85, sensors at a depth of 122 meters in a sea state 2.

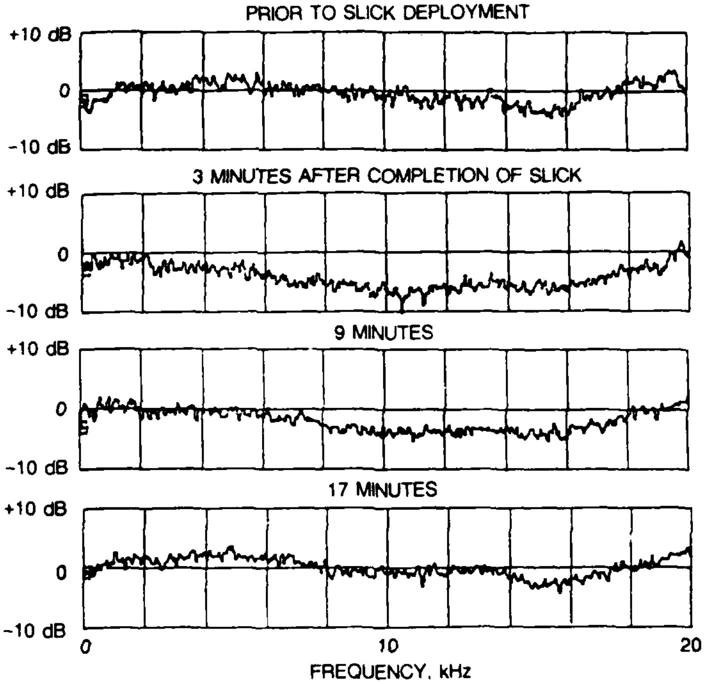

Figure 10. Spectral ratios (slick/no slick) for AROSURF-MSF, *sensors at a depth of 18 meters in a sea state 6.*

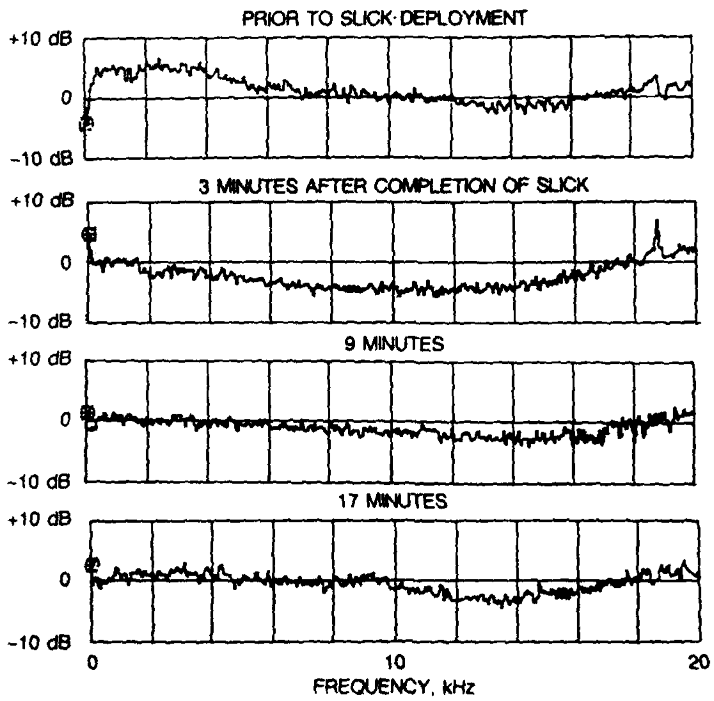

Figure 11. Spectral ratios (slick/no slick) for AROSURF-MSF, sensors at a depth of 122 meters in a sea state 6.

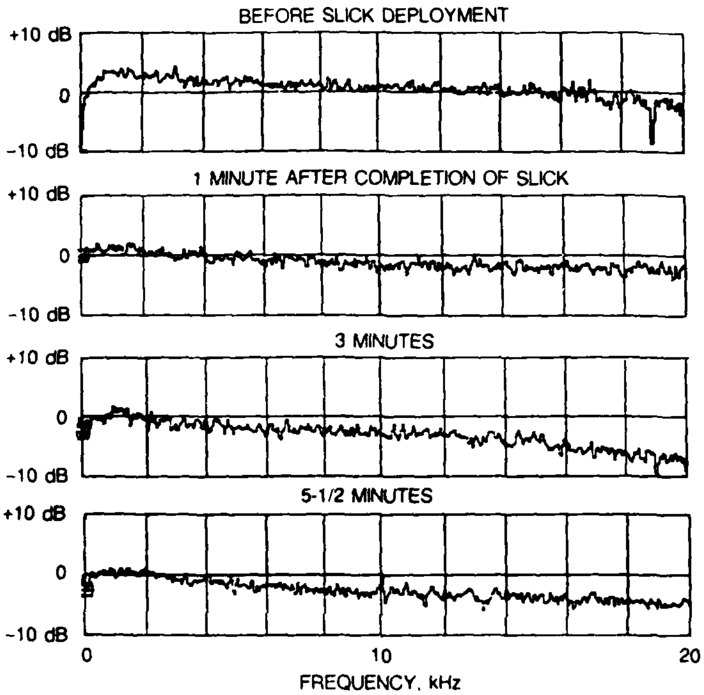

Figure 12. Spectral ratios (slick/no slick) for ADOL-85, sensors at a depth of 18 meters in a sea state 6.

c. There was little difference between the noise-quieting measurements at the 18- and 122-meter hydrophone depths. This agreed with the model predictions for a slick of about 300-meter radius and a historically representative velocity profile.

d. The occasional "spikes" in the spectral-ratio plots are due to various types of active sonars (navigational, fish finding, etc.) in the vicinity of one or the other buoys.

e. The initial ambient-noise attenuation of 6 to 8 dB above 5 kHz continually declines over the next 90 minutes until the slick either totally breaks up or simply drifts away from the initial underlying hydrophones. The observation that the slick appeared to remain intact some 30 minutes after the end of any measured noise-quieting effect indicates the latter. The drift velocities of surface films have been found (Huhnerfuss and Garrett, 1981) previously to be about 3 to 4 percent of the wind velocity, which could account for the relative drift hypothesized.

Experiment II utilized two slicks, AROSURF-MSF and ADOL-85, in sea state 2 (about 10 knots) conditions. Figures 6 and 7 show the results of the AROSURF-MSF slick which are generally similar to those obtained in the previous experiment. Unfortunately, much of the data were obscured by the presence of a "hump" in the spectral ratios from 8 to 14 kHz, which was occasioned by the presence of a school of squealing porpoises in the vicinity of the test hydrophones. The processing of time intervals later than 79 minutes on the 122-meter test buoy to determine when the film effect was no longer recognizable, was precluded by RF interference. Figures 8 and 9 show the corresponding spectral ratios for the ADOL-85 slick. The same general observations apply to these results (including the presence of porpoises), but note the increased attenuation (i.e., up to 10 dB initially) at the highest frequencies recorded. Since it is impossible to repeat slick shape and positioning relative to the sensors for each experiment, differences in spectral ratios cannot generally be attributed to differences in the intrinsic behavior of the films. However, observations at higher sea states (see figures 10 and 11) of a similar difference in performance between the two chemicals, suggest a trend which should be accounted for.

One possible interpretation is that, while the two different chemicals provide similar surface-smoothing effects, their direct impact on bubbles may be quite different. That bubbles can have a dramatic influence on the propagation of sound can be strikingly demonstrated (Farrell, McKenzie, and Parker, 1969) by simply tapping on a glass filled with carbonated beverage before and after it is gently shaken. In the ocean, the bubble population is known (Wu, 1981) to increase rapidly with wind velocity, presumably due to more widely spread and violent wave breaking. Farmer and Lemon (1984) have found that for sufficiently high wind speeds, the noise levels at the high frequencies measured at 14.5 and 25 kHz actually decreased with increasing wind speed. Since there are no known noise-producing mechanisms which would decrease with increasing wind speed, Farmer and Lemon hypothesized no alteration in the noise-generating mechanism, but an increasing attenuation at these

frequencies due to a thin layer of bubbles close to the surface. They further acknowledge that the acoustic properties of bubbles maybe altered by surface contamination. Medwin (1977) has found a significant increase in the fraction of larger bubbles near the surface when in the presence of natural sea slicks. Laboratory measurements by Garrett (1967) have shown that water insoluble surface-acting materials, when compressed, enhance the immediate breaking of small bubbles. The amount of compression necessary before antifoaming behavior is realized depends on the chemical makeup of the surfactant. Laboratory tests are necessary to confirm whether the films in question affect bubbles differently. If so, this could explain their different acoustic performance at high frequencies.

While experiments I and II were conducted in the relatively calm waters off the coast of southern California, experiment III was conducted approximately 60 nautical miles offshore Iceland to observe the acoustic impact of the films at high sea states. The first test was conducted in a strong gale (sea state 6, about 40- to 50-knot winds), while the second occurred in near gale (sea state 5, about 30-knot winds) conditions. Due to the strong winds, the slick emplacements were immediately upwind from the hydrophone buoys, so the slick would drift over them. Therefore, when measurements were taken immediately after slick deployment (see figure 12), the spectral ratios are observed to first decrease (as the slick drifts over the sensors) and then increase, returning to their preslick values (as slick breaks up and/or drifts away). Estimated slick-drift rates were 1 to 2 knots. As expected due to the adverse weather conditions, slick persistence in the vicinity of the test buoys was relatively brief (10 to 15 minutes). Whereas natural sea slicks have been observed (Garrett, 1980) to withstand sustained wind speeds of only 5 to 7 meters per second, artificial slicks have been maintained with wind speeds as great as 13 meters per second (Broecker, Petermann, and Siems, 1978) if excess film-forming material could be supplied to repair ruptures in the slick. In the high winds (about 20 meters per second) off Iceland, the film did not remain cohesive but soon developed streaks which completely obscured its leeward perimeter.

For the record, during the short time the film was intact, it was the consensus of the crew that there was less whitecapping occurring within the slick. Franklin (1774), Barger et al. (1970), and Toba and Kunishi (1970), have observed similar phenomenon, but at presumably lower sea states. These results suggest that films could be useful in air-sea rescue operations. The last such recorded[1] instance was in 1914, when passengers from the hospital ship S.S. Rohilla were rescued while the calming effect of oil spread from a lifeboat persisted. Unfortunately, because a low-cloud ceiling and heavy overcast made visual confirmation difficult, the present observations cannot be conclusive.

[1] The Lifeboat 22, 198 (1915).

Figures 10 and 11 show the spectral ratios for the tests at the highest sea state (about 6) and for the AROSURF-MSF slick. Note that for both depths, the ratio prior to slick deployment is not a uniform 0 dB, most probably due to the variable squalls lashing the area. Figure 10 shows an attenuation in the spectral ratio up to 9 minutes after slick deployment, with the ratio having essentially returned to its preslick shape after 17 minutes. The 122-meter depth results in figure 11 are similar in character. The maximum deflection of the spectral ratio from its preslick values appears to be 5 to 6 dB for the 18-meter depth sensor, and 4 to 5 dB for the 122-meter depth sensor, from about 6 to 12 kHz. Figure 12 shows the results (recorded simultaneously) for the ADOL-85 slick. Here, also about a 5-dB reduction of the spectral ratio at frequencies greater than 8 kHz is initially observed ($5\frac{1}{2}$ minutes after slick deployment), after which the hydrophone beneath the slick failed. The 122-meter hydrophone buoy failed from the outset. Unfortunately, all spare hydrophones had already been expended to replace the original buoys in the AROSURF-MSF slick.

In the second test off Iceland (sea state 5), similar results were observed (i.e., a 4- to 6-dB reduction) for the slick composed of AROSURF-MSF with the exception of an unexplained anomaly from 4 to 8 kHz. The latter may have been helicopter-noise related, or some other unknown (e.g., biologics) contamination. Because of worsening weather conditions, for the second test, the helicopter immediately began dispensing the slick after deploying the test hydrophone. Therefore, no preslick data are available to help determine the origin of this anomaly. Only relatively minor acoustic attenuation (1 to 2dB) was observed for the neighboring ADOL-85 slick, which suggests that the entire slick never drifted over the hydrophones. It was noted that the ADOL-85 slick was not visible when the aircraft observers were close enough overhead to see the dye markers attached to the hydrophone buoys.

Because of the marginal control that could be exercised, the primary objective of these high-sea-state tests was only to determine if roughly similar trends found in the low-sea-state data, could be recognized. This indeed appears to be the case.

Finally, it should be noted that in an experiment performed off the coast of southern California in about a sea state 0, where the sea was glassy smooth, no effect of the film could be discerned. Not only was there for the first time no impact observed on the ambient noise, the slick's presence was no longer visibly inferable. As previously mentioned, under most conditions the film's attenuation of capillary waves decreases the average wave slope, thereby producing a light reflectance anomaly. The film may appear lighter or darker than the surrounding rippled water, depending on the viewing angle, with respect to the sun. The mechanisms involved in sunglint, including observations on the visibility of oil slicks have been developed by Cox and Munk (1954). Since the location of the film could not be directly determined, there is no assurance that the hydrophones were positioned directly below. However, there are reasons to believe that the films are simply not effective at these low sea states.

Broecker et al. (1978) have studied the effect of oleyl alcohol (ADOL-85) in a wind-wave tunnel to determine its influence on CO_2 exchange. Below about 2 meters per second, no difference in mass transfer is observed between surfaces with and without the film. It was precisely this speed (2 meters per second) that capillary waves were first observed to develop in the absence of the film. With the film present, damping of small waves and a consequent reduction in CO_2 transfer were observed only at higher speeds. It also seems reasonable that for the films to have any acoustic impact, there must first exist some threshold of local surface agitation.

POSSIBLE MECHANISMS

What is particularly intriguing about the thin film results reported here is that whatever noise mechanism the film undermines, this mechanism appears to be present throughout a wide range of sea states (1 through 6). Therefore, a better understanding of how monomolecular films reduce underwater ambient noise originating at the surface of the ocean should lead to a better understanding of ocean ambient noise in general. While a strong correlation has been found (Kerman, 1984; Knudson, et al., 1948; Wenz, 1962) between the agitation of the sea surface and ambient noise between 0.5 and 25 kHz, the actual mechanism through which the noise is generated remains uncertain. As Urick (1967) and Wilson (1980) point out, breaking whitecaps and spray, the most obvious source of sea surface noise, cannot be solely responsible since ambient-noise levels increase rapidly from sea state 0 to sea state 2 in the absence of whitecap formation.

While ambient-noise-spectral levels associated with the sea surface are dependent on wind speed, their spectral shape generally are not, suggesting some similar process occurring at the local surface. For sea states neither too low (Wenz, 1962) nor too high (Farmer and Lemon, 1984) the spectrum from 0.5 to 25 kHz exhibits nearly a constant -6 dB/octave slope. Deviations from this spectral shape are presently not attributed to alterations in the noise-generating mechanism itself. At the lowest sea states there is presumably some threshold of agitation for surface-noise mechanisms to be initiated. Below this threshold ambient noise would be characterized by distant sea states. Under these conditions, where the surface-related noise must now propagate much farther, it would be anticipated that the spectrum would fall off faster at higher frequencies where adsorption losses are greater. This is supported by a compilation of measurements reported by Kerman (1984) where for wind speeds less than 5 meters per second (about sea state 1) there is observed proportionally less high-frequency noise. These observations further support preceding arguments that the films would not be expected to have noise-quieting effects at the lowest sea states. The spectral anomalies at the higher sea states associated with a surface bubble layer has previously been discussed.

FILM EFFECT ON SPLASH DYNAMICS

Franz (1985) has found that splash noise exhibits a spectrum slope of about -6 dB/octave. Since the dynamics of splashing is in part governed by surface tension, which is known to be dramatically changed by the films, a preliminary study was initiated to investigate whether the films directly affect the dynamics of the splash.

Figure 13 is a diagram of the apparatus used. A drop initially rests on an hourglass held in place by a rubberband. When the rubberband is cut the hourglass swings away from the drop which then falls to the liquid-filled beaker below. Along its downward journey the drop interrupts a laser beam which triggers a flash with a variable delay time, thereby allowing different parts of the splash evolution to be recorded on film. A series of pictures of different drops, each with similar initial conditions but with slightly longer delays, will then provide the complete splash evolution. The pictures in figures 14a, b, and c were achieved in this fashion. Here 0.3 cc drops fall a distance of one meter to the beaker below. Such large drops could be attained only after coating the hourglass with a hydrophobic material (it was found by Worthington (1908) that the carbon from a burning candle worked well).

High-speed recordings (4000 frames per second) indicate that filmed surfaces dampen ripples emanating from the drop impact point. However, in a series of photographs illustrating different stages of the splash evolution, essentially no difference was found between splashes without (e.g., figure 14a) and with film (e.g., figure 14b) for equal time delays. Davies and Vose (1965) have found that soluble surfactants at frequencies less than 450 Hz, may exhibit a relaxational effect due to desorption and adsorption of the film which short circuits the surface pressure gradients and thereby reduces the damping coefficient. As the chemical in figure 14b is almost insoluble, 2 ppm at equilibrium, its ineffectiveness is more likely due to its relatively low-spreading rate (34-40 centimeters per second) during such a quick event (about 1/1000 second). The inability of monomolecular films to influence surface-tension-governed phenomena over short time durations was first reported by Lord Rayleigh (1890). Through observing the frequency of oscillation of liquid jets issuing from an elliptical opening, Rayleigh determined that the surface tension of a liquid contaminated with soap within the first hundredth of a minute was no different than pure water because the surface contamination had no time to form.

Splash dynamics were found to be dramatically affected by small amounts of polymer. Figure 14c shows that a drop containing 50 wppm of separin (a common drag-reducing polymer) falling into the same liquid produces much less, if any, spray. The New York City Fire Department uses similar long-chain polymers to increase water jet coherence (Hoyt and Taylor, 1977), i.e., reduce spray. The suppression of secondary spray with the addition of polymer suggests future work to isolate its acoustic signature from the actual impact of the water drop on the surface and the resulting bubble volume pulsations.

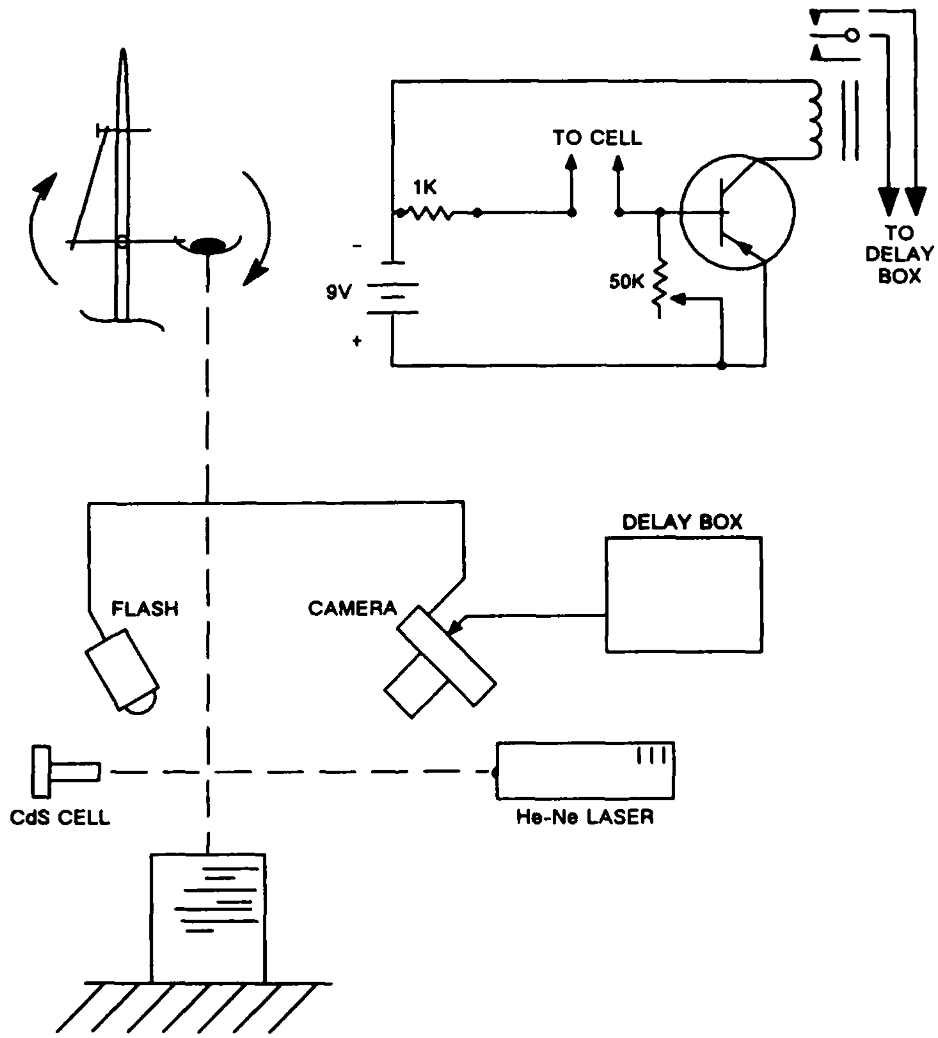

Figure 13. Experimental setup for taking splash pictures.

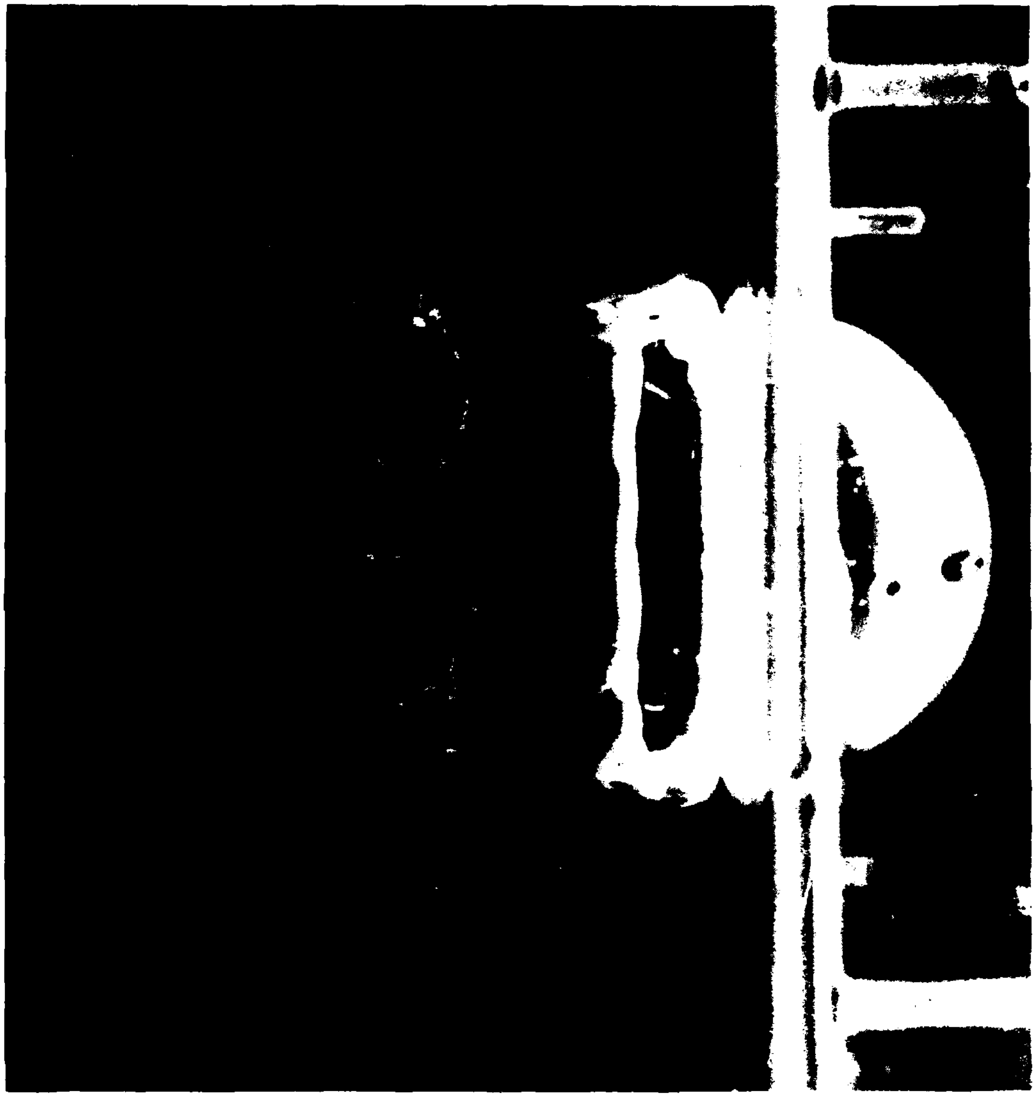

Figure 14a. Water splash.

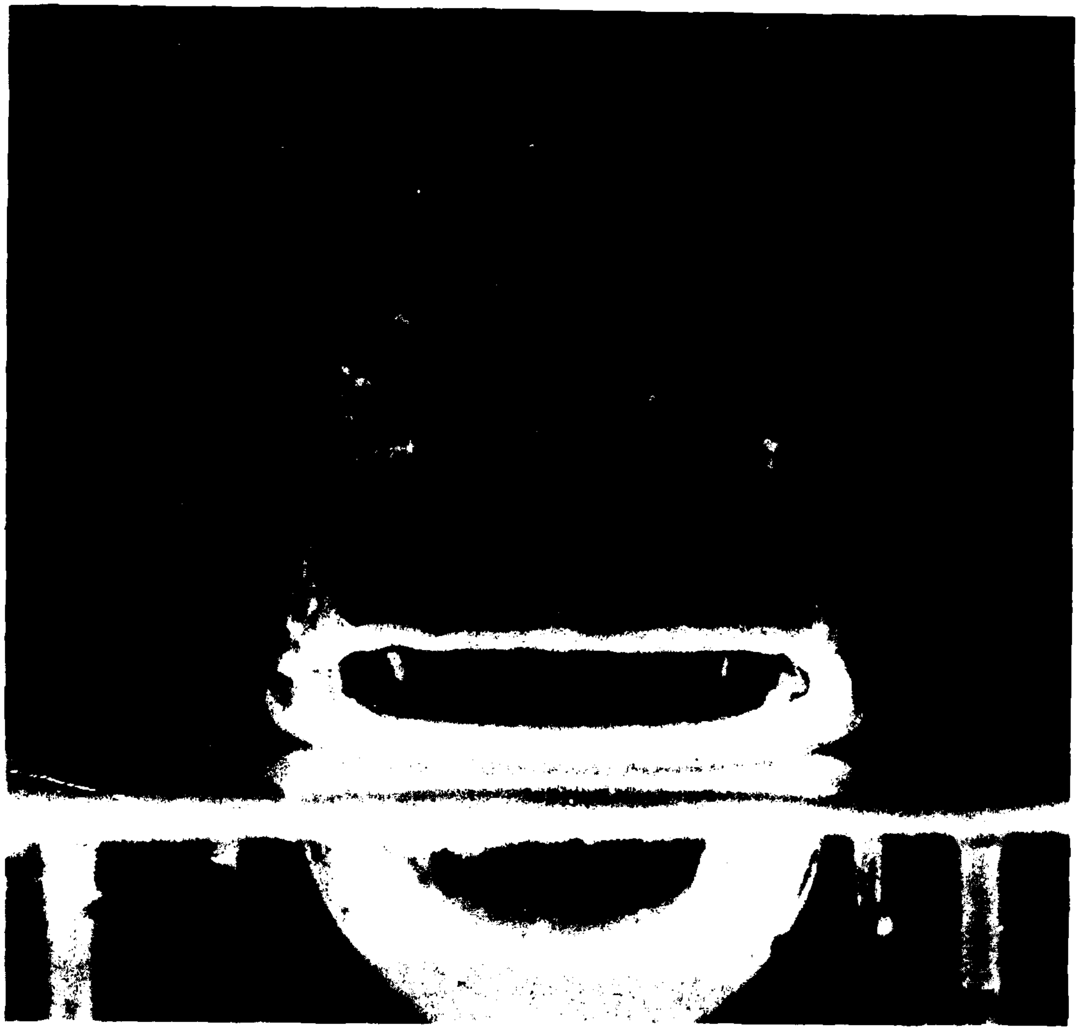

Figure 14b. Water splash with film, the same time delay as in figure 14a.

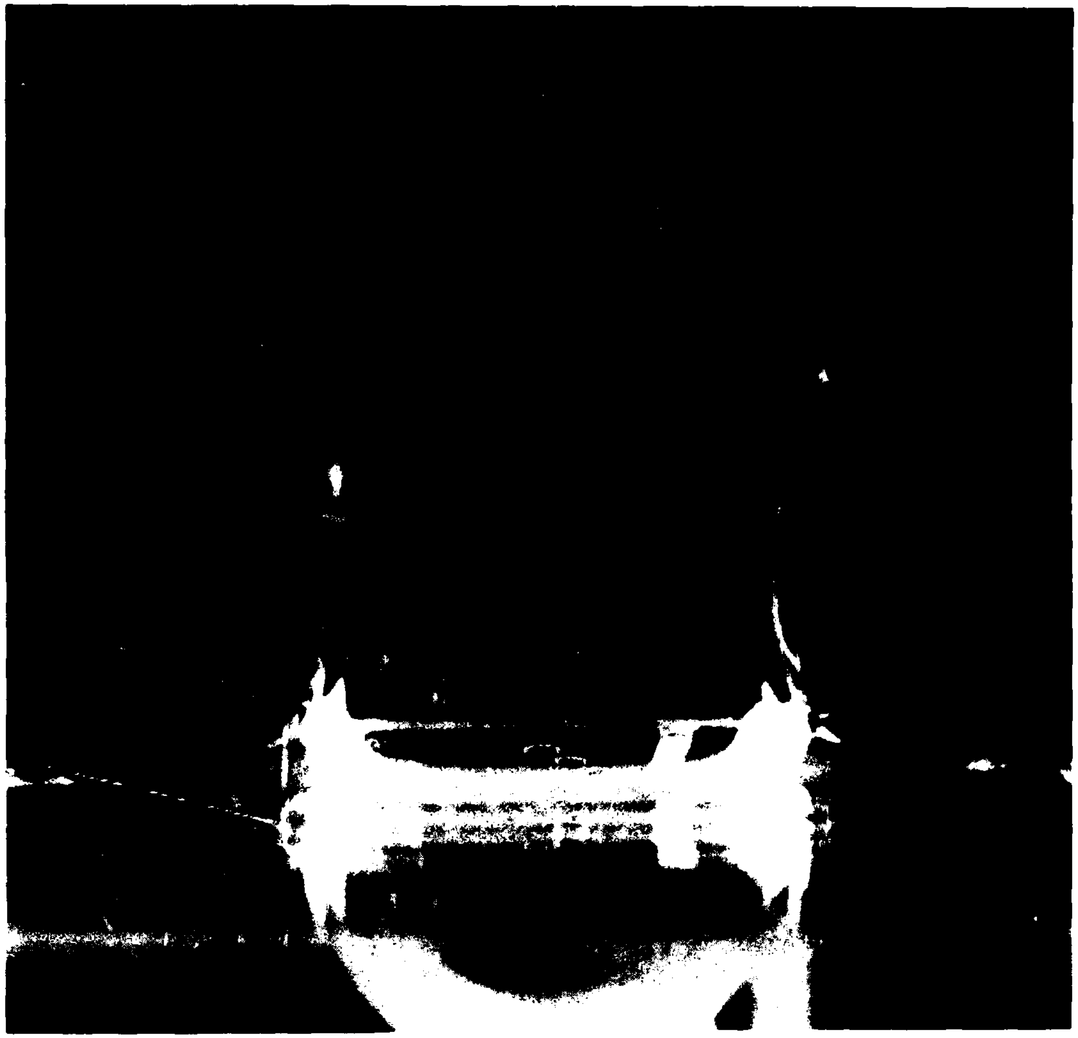

Figure 14c. Water spash with 50wppm separin, the same time delay as in figure 14a.

FILM EFFECT ON THE BREAKING OF SMALL GRAVITY WAVES

The following at-sea experiments were in collaboration with Dr. Victor Anderson and Garr Updegraff of the Marine Physical Laboratory and Scripps Institute of Oceanography. Their recent work has been directed towards a better understanding of the origin of low sea state ambient noise through correlating visual observations of events occurring at the sea surface with their accompanying underwater noise. They have designed an instrument package which floats about a meter below the surface. The package consists of an underwater video camera surrounded by four omnidirectional hydrophones through which activity on the ocean surface can be tracked both visually and aurally from below. To minimize self-noise, the instrument package was tethered to a 1-kilometer cable attached to a barge anchored several miles off the coast of southern California.

Previous experiments in about sea state 2 had found that ambient noise just beneath the ocean surface to be characterized by intermittent events of tonal quality. Occasionally, the video camera, which recorded disturbances on about a 2-meter diameter of the ocean surface, would witness such an event. These were composed of small, breaking, gravity waves which would encapsulate air as they overturned, leaving a trail of bubbles along their path. It appears that the sound is initiated when the air is first pinched off by the overturning wave. Minnaert (1933) and Strasberg (1956) have noticed a similar phenomenon in the context of a bubble closing at the end of a tube or nozzle. Strasberg's calculations show that appreciable sound is radiated only when the bubble is in its zero mode of simple volume pulsation. Furthermore, if the amplitude of the oscillations is small compared to the mean bubble radius, then the various surface harmonics can be considered independent of each other. In these tests, it was also observed that the bubbles remaining after their inception generally did not produce additional noise.

On two separate days, under sea state 2 conditions (about 10-knot winds with occasional waves breaking), simultaneous visual and aural recordings were taken before and after a small quantity (about 2 gallons) of oleyl alcohol was dispensed above the instrument package. As the film was deployed measurements were obscured by the dispensing boat; however, on its return to the barge, the film's impact was immediately apparent. The intermittent surface sounds discussed previously were conspicuously reduced as were the visual observations of small-scale wavebreaking. Unfortunately, propeller cavitation which changed with the inhomogeneity of ship traffic dominated the total noise power. Therefore, it was often observed that the total noise power was actually greater with the film present. In an attempt to quantify the film's impact on the naturally occurring intermittent surface noise (which comprised only a small percentage of the total data recorded), the following procedure was adopted. First, rms values for several sections of tape (1 to 2 minutes), where the background shipping noise was fairly constant, were calculated. A threshold was then set at twice this rms value. To discriminate short-duration sounds of unknown origin (presumably biologics), a 6-millisecond hold time was also used. Generally, the noise associated with the small waves breaking persisted more than 10 milliseconds. Using this procedure it was found that when the slick was present, intermittency was reduced between 80 and 90 percent.

It is hoped that future experiments of this nature will be conducted where there is less noise due to ship traffic. Moreover, sea states between 0 and 2 would be preferred. As previously mentioned, the noise mechanisms responsible for the steady increase in ambient noise with increase in windspeed, before the appearance of breaking waves, remains a mystery. The fact that the films are exceedingly effective in at least part of this regime (sea state $1\frac{1}{2}$) suggests that the mechanism must be governed to some extent by surface tension.

For small capillary waves whose restoring force is due solely to surface tension, Crapper (1957) has found an exact mathematical solution of arbitrary amplitude. These waves, unlike gravity waves, have profiles that peak downward. In this scenario, the waves are predicted to "break" when the sides of adjacent waves touch, thereby pinching off a two-dimensional tube of air. As this configuration is unstable, the tube is expected to breakup into smaller spherical bubbles, presumably producing a significant amount of noise in the process. Schooley (1958), using highspeed motion pictures, has observed in a modest water-wind tunnel (best results reported were for a 13-inch fetch with about a 6-meter-per-second wind) wave profiles similar to that predicted by Crapper. Unfortunately, the maximum crest-to-trough amplitude observed by Schooley was about 0.5 wavelength, whereas "breaking" is predicted at a height-to-wavelength ratio of 0.73 (for comparison, breaking gravity waves occur at a ratio of 0.14). The actual enclosure of air bubbles at the capillary wave trough has been documented by Toba (1961, p. 320) in a large wind flume (21.6 meters) beginning at a mean speed of 7.5 meters per second. He states, "The water surface, as seen from beneath, looks like a ceiling of a stalactite grotto. As Crapper suggested for pure capillary waves, air bubbles are enclosed at the troughs, and scatter into the water..." Furthermore, Toba calls attention to the profound consequences that a change in the surface tension of sea water could have on this mechanism. If at larger fetches this phenomenon could appear at lower windspeeds, then clearly it is an attractive candidate for a low sea state ambient-noise source, which would be affected by the film. Recent work by Longuet-Higgins (1988) has provided much needed mathematical precision to many of these ideas.

Another possible mechanism for low sea state noise, which would be sensitive to the films and display the expected spectral slope, is simply the overturning of small gravity waves. At the small scales envisioned, these "breaking" waves would not create enough bubbles to be easily perceived from a ship's deck. However, the perspective from a platform right at the ocean's surface, as provided by a surfboard for example, suggests to at least one of the authors that this microbreaking does indeed occur. Similar observations of air entrainment by lapping small waves have been observed[2] in laboratory wind-wave facilities. Toba and Kunishi (1970) have reported the entrainment of air bubbles at the crests of small wavelets upon a stretch of ocean on the leeward side of an anchored ship. Simultaneous video and hydrophone recordings at the low sea states of interest should be able to tell if either of these mechanisms (gravity or Crapper "breaking" waves) are important sources of ambient noise.

[2] Personal conversation with Dr. Bruce Lake, TRW, 1987.

CONCLUSIONS

The experiments described herein demonstrate the effect of monomolecular films on underwater ambient noise. It was found that local surface-generated noise was dramatically reduced, from 2 to at least 20 kHz over a wide range of sea states ($1\frac{1}{2}$ to 6). It is believed that through studying the impact of films on ocean ambient noise, fundamental insight regarding the noise-producing mechanisms will result. In laboratory tests, the same films were found to have no direct effect on splash dynamics, although indirectly they presumably affect the rate of splashing through their documented reduction of capillary waves, foam stability, and inhibition of breaking gravity waves. Simultaneous video and aural recordings of events occurring on the sea surface for sea state 2 conditions show that the film greatly reduced (80 to 90 percent) the number of small breaking gravity waves which appeared to be the source of the intermittent surface noise.

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